

# ENGINEERING SERVICES FOR THE NEXT GENERATION NUCLEAR PLANT (NGNP) WITH HYDROGEN PRODUCTION

# Test Plan for S-I Hydrogen Production System (HPS)

Prepared by General Atomics
For the Battelle Energy Alliance, LLC

Subcontract No. 00075309 Uniform Filing Code UFC:8201.3.1.2

**GA Project 30302** 

















# GA 1485 (REV. 08/06E)

# **ISSUE/RELEASE SUMMARY**

☐ R&D ☐ DV&S ☑ DESIGN	APPVL LEVEL		C QA LEVEL	SYS	DOC. TYPE	PROJEC	CT DOCUMI	ENT NO.	REV
☐ T&E	5	0	l	44	TPL	30302	2	911144	0
TITLE:				J					<u> </u>
Test	: Plan for	· S-I Hy	ydrogen Produc	ction System	(HPS)				
					APPRO	OVAL(S)	· · · · · · · · · · · · · · · · · · ·		
CM APPROV DATE		REV	PREPARED BY	ENGINEER	RING	QA	PROJECT	REVISION DESCRIPTION W.O. NO.	ON/
ISSUED 4	ī>		R.	D.S.81		At !	Manuel		17
DEC 0 9 2	.008	4	Buckingham	A. Shen	oy Y K	. Partain	J/ Saurwein	Initial Issu A30302-01	
	]	FOR	J. Opperman						
									-
CONTINUE ON		711254							
CONTINUE ON	GA FURM	1485-1						NEXT INDENTU	
								N/A	
									-
								COMPUTER PRO	)GRAM
								N/A	
THIS DOO IN CONFI PART AN CONTAIN	FIDENCE. ND WILL I NED HERE	IS THE PEXCEPT BE RETI	PROPERTY OF G T WITH THE WRIT TURNED UPON R	ITTEN CONSEN REQUEST OR	NT OF GA, (1) WHEN NO LO	THIS DOCUL	MENT MAY NOT	UMENT OUTSIDE GA F BE COPIED IN WHOI PIENT AND (2) INFOR ENT ONLY FOR THE P	LE OR IN
NO GA P	ROPRIET	ARY INF	FORMATION					PAGE ii OF *	

# **TABLE OF CONTENTS**

1	INTRODUCTION	1
1.1	HPS Description	3
1.2	Scope	
1.3	Purpose	
1.4	Background	5
2	APPLICABLE DOCUMENTS	7
3	TEST PROGRAM TO ADVANCE TO TECHNOLOGY READINESS LEVEL (TRL) 6	8
3.1	Test Objective	8
3.2	Test Description	
3.3	Test Conditions	9
3.4	Test Configuration/Set-up	9
3.5	Test Duration	
3.6	Proposed Test Location	
3.7	Pilot Plant Test Measured Parameters	
3.8	Data Requirements	
3.9	Test Evaluation Criteria	
3.10	Supplementary Tests	
4	TEST PROGRAM TO ADVANCE TO TRL 7	
4.1	Test Objective	
4.2	Test Description	
4.3	Test Conditions	
4.4	Test Configuration/Set-up	
4.5	Test Duration	
4.6	Proposed Test Location	
4.7 4.8	Measured Parameters  Data Requirements	
4.0 4.9	Test Evaluation Criteria	
4.10	Supplementary Tests	
<del>5</del> . 10	TEST PROGRAM TO ADVANCE TO TRL 8	
<b>5</b> 5.1	Test Objective	
5.1 5.2	Test Description	
5.2 5.3	Test Conditions	
5.4	Test Configuration/Set-up	
5.5	Test Duration	
5.6	Proposed Test Location	. 15
5.7	Measured Parameters	. 15
5.8	Data Requirements	. 15
5.9	Test Evaluation Criteria	. 16
5.10	Supplementary Tests	. 16
6	TEST DELIVERABLES	. 17
7	COST, SCHEDULE, AND RISK	. 18
7.1	Cost	. 18
7.2	Schedule	
7.3	Risk	. 19

1 8	DESIGN DATA NEEDS	21
	LIST OF FIGURES	
Figure 2 Figure 3 Figure 4	SI based HPS-HTGR Concept	2 4 4
	LIST OF TABLES	
Table 2. Table 3. Table 4. Table 5. Table 6.	Nominal Prototype Plant Design Parameters  Applicable Documents  Pilot Plant Performance Criteria  Engineering Demonstration Plant Performance Criteria  Prototype Plant Performance Criteria  Costs Estimates for SI-Based HPS Testing  Shaw Group Design Data Needs for the HPS	7 10 13 16 18

#### 1 INTRODUCTION

The Next Generation Nuclear Power (NGNP) program is a cooperative government-industry effort aimed at demonstrating the technical, licensing, operational, and commercial viability of High Temperature Gas Reactor (HTGR) technology for production of process heat, electricity, and hydrogen. Idaho National Laboratory (INL), on behalf of the Department of Energy (DOE), is leading the demonstration of HTGR technology for economic and reliable electricity and hydrogen production.

The NGNP program will follow an integrated approach in the development of the design and design documentation. This approach is aimed at continually driving the requirements to a point where a procurement specification can be prepared for each component; in this case, the Hydrogen Production System (HPS).

This preliminary test plan addresses the design considerations of the HPS for the NGNP. Hydrogen could be produced through the Sulfur-Iodine (SI) thermochemical cycle. The SI cycle may been chosen because of its high efficiency and its potential for further development. The HPS will be a key component in the NGNP. Figure 1 shows a conceptual design for the HPS coupled with the HTGR.

As shown in Figure 2, the heat required to drive the prototype SI process is supplied by the HTGR. The plant could consist of a HTGR module of up to 600 MW(t) coupled to an Intermediate Heat Exchanger (IHX) to transfer a portion of heat to a secondary helium loop. This heat is then transferred to the prototype SI-based HPS. Waste heat is rejected using cooling towers in a manner similar to that for electricity-producing plants. In addition to the heat required to drive the SI process, the plant requires approximately 7 MW(e). Most of this electricity is needed to power pumps and compressors that are part of the HPS design. For this study, it is assumed that the HPS plant is part of an energy park that provides necessary electricity. Nominal prototype hydrogen plant design parameters are given in Table 1. At a 90% capacity factor, the plant produces up to  $3.3 \times 10^3$  metric tons of hydrogen per year at an efficiency of 45.0% (based on the higher heating value of hydrogen) with a product gas pressure of 300 psig.

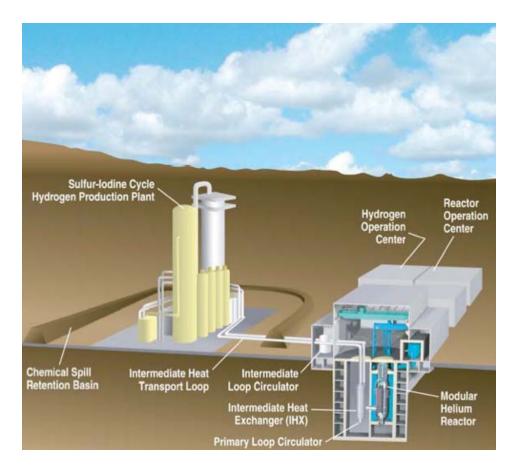


Figure 1. SI based HPS-HTGR Concept

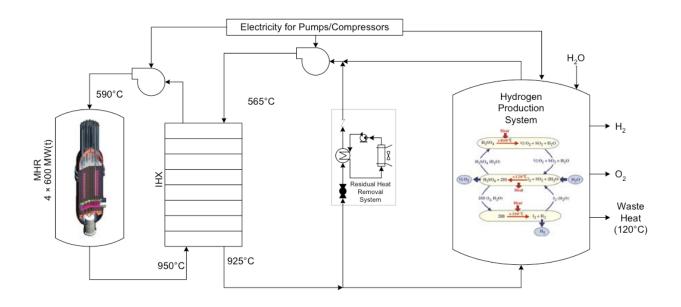


Figure 2. SI based HPS-HTGR Process Schematic

**Table 1. Nominal Prototype Plant Design Parameters** 

Hydrogen Production System	
Peak process temperature	750°C - 900°C
Peak process pressure 525 psig	
Product hydrogen pressure	300 psig
Annual hydrogen production* 3.3 x 10 <sup>6</sup> kg	
Plant hydrogen process efficiency**	45.0%

<sup>\*</sup> Based on an overall plant capacity factor of 90%

# 1.1 HPS Description

The SI cycle is divided into three separate steps:

- 1. Sulfuric acid concentrator and decomposer
- 2. Bunsen reaction
- 3. Hydrogen iodide concentrator and decomposer

Water thermally dissociates at significant rates into hydrogen and oxygen at temperatures approaching 4000°C. As indicated in Figure 3, the SI process consists of three primary chemical reactions that accomplish the same result at much lower temperatures. The process involves decomposition of sulfuric acid and hydrogen iodide, and regeneration of these reagents using the Bunsen reaction. Process heat is supplied at temperatures equal to or greater than 750°C to concentrate and decompose sulfuric acid. The exothermic Bunsen reaction is performed at temperatures below 120°C and releases waste heat to the environment. Hydrogen is generated during the decomposition of hydrogen iodide, using process heat at temperatures greater than 300°C. Figure 4 shows a simplified process flow diagram of the SI cycle. The product hydrogen gas is produced at a pressure of 300 psig.

<sup>\*\*</sup> Based on the higher heating value of hydrogen (141.9 MJ/kg)

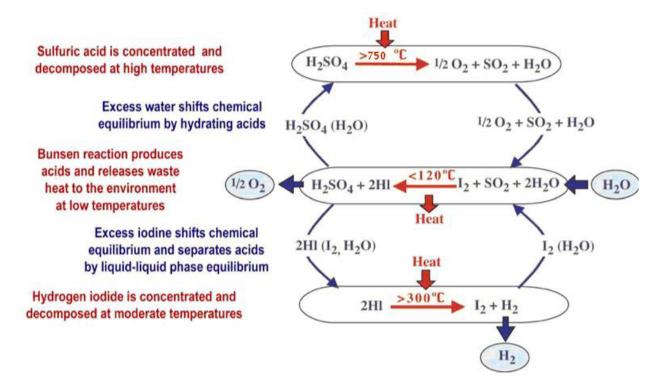


Figure 3. The SI Thermochemical Water Splitting Process

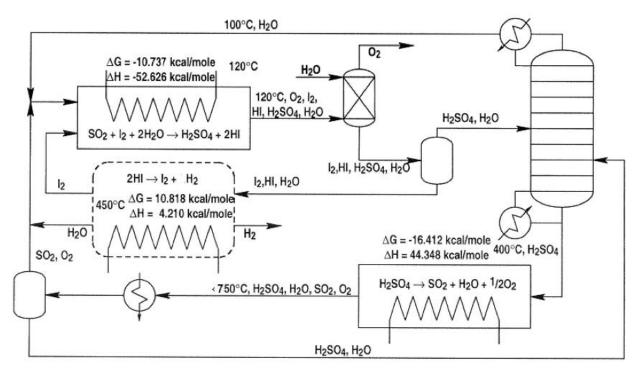


Figure 4. Simplified SI Process Flow Schematic

# 1.2 Scope

The scope of work includes the development tasks necessary to produce acceptable HPS subsystem hardware for the NGNP. The testing program will define the component configuration by starting with the conceptual design, and then progress through various stages until an entire prototype assembly will be tested.

Current work is underway to bring the SI cycle development to TRL 5. The goal of this effort is to produce 100 standard liters of hydrogen per hour with each section running in an integrated mode. This test plan focuses on the development of a pilot scale plant (70kW) for advancement from Technology Readiness Level (TRL) 5 to TRL 6. This will be followed by the development of an engineering scale plant (1.5MW) for achieving TRL 7. Finally, the prototype plant (15MW) will be integrated with the NGNP achieving TRL 8 after successful testing.

# 1.3 Purpose

The purpose of this test plan is to define the NGNP HPS program and to describe the individual tests and their interrelationship.

Any change in the HPS from previous experiences requires the requalification of the design. In general components of the HPS are evolutions from a proven technology and experience basis, but will be uniquely configured and sized for the NGNP arrangement.

The development of a complete testing program will be design dependent; therefore this test plan document is prepared for guidance only.

# 1.4 Background

The US DOE research and development effort on the SI cycle has been done primarily in collaboration with the French Commissariat à l'Energie Atomique (CEA) under an International Nuclear Energy Research Initiative (I-NERI) agreement since 2003. There is close coordination between the project participants in developing the three component reaction sections: the H<sub>2</sub>SO<sub>4</sub> decomposition section, done by Sandia National Laboratory (SNL); the HI decomposition section, done by GA; and the Bunsen reaction equipment, provided by CEA. Each participant has designed and constructed their respective section and is working to integrate them in a SI Integrated Laboratory-Scale (ILS) experiment. Integrated experimental operations began in late 2007. All experimental equipment was transported to the GA site for assembly and testing. Through 2004 and 2005, experimental work in glass equipment was conducted to evaluate and choose appropriate methods for carrying out the reactions in each section. Design work in 2006 allowed for lab-scale devices to be constructed in 2007 from engineering materials that are expected to be used in a pilot-scale hydrogen production facility scheduled for operation beginning in 2012. These lab-scale devices make up the equipment of the ILS experiment.

Unlike previous demonstrations elsewhere, the ILS experiment operates at temperatures and pressures expected to be seen at larger scales. The ILS test is expected to operate at least through the end of 2009.

The highly corrosive nature of the chemical streams in the SI process has led to significant research work in the area of materials compatibility. Early screenings showed that alloys of tantalum appeared suitable, and current work is exploring long-term performance and corrosion resistance of materials stressed or machined in ways that materials of construction for larger scale plants will experience. Devices for testing materials under simplified flow conditions have been built. The ILS experiment will also be a test bed for corrosion resistance of engineering materials during its operation.

Modeling and simulation of the SI process is necessary to predict thermodynamic efficiency, and to size equipment for cost estimation. Any uncertainties in the model are retained in efficiency and cost calculations. Work at Clemson University funded under a NERI grant is collecting thermodynamic data that will continue to improve the robustness of modeling and simulation efforts.

The SI-based hydrogen plant can be designed to limit the gaseous and liquid chemical waste streams to very low levels. The only feedstock is water, and the only products are hydrogen and oxygen. The most hazardous process materials (e.g., sulfuric acid and iodine) are fully contained and recycled. In fact, the SI plant appears to have the potential to be a nearly "zero-discharge" facility which would be a worthy design goal. The majority of waste produced will be spent catalyst. The oxygen product stream will likely contain traces of sulfur dioxide, which may require polishing by caustic scrubbing. A small quantity of corrosion products (mainly metal sulfates) will also be generated. At the end of its operational lifetime, the physical plant will represent the ultimate "by-product" of electricity and hydrogen production, and both the reactor plant and the hydrogen plant will have to be decontaminated and decommissioned.

# 2 APPLICABLE DOCUMENTS

**Table 2. Applicable Documents** 

Document Number	Title
911107	GA NGNP and Hydrogen Production Preconceptual Design Studies Report
PC-000543	GA NGNP Umbrella Technology Development Plan
	High Efficiency Generation of Hydrogen
GA-A24285	Fuels Using Nuclear Power: Final Technical Report for the Period August 1, 1999 Through September 30, 2002
GA-A25401	H2-MHR Pre-Conceptual Design Report: SI-Based Plant

# 3 TEST PROGRAM TO ADVANCE TO TECHNOLOGY READINESS LEVEL (TRL) 6

TRL 6 definition: Components have been integrated into a subsystem and demonstrated at a pilot scale in a relevant environment.

A SI pilot plant will be constructed at a site to be determined. The plant will be electrically heated and it will be composed of materials of construction expected to be used for use in full-scale plants.

An effort is currently underway to bring the SI process development to TRL 5. An Integrated Laboratory Scale (ILS) device is designed to produce 100 normal liters per hour (nlph) under prototypical temperatures and pressures. The device is in operation at the General Atomics site in San Diego. CEA (France) is responsible for providing equipment and manpower to operate the Bunsen reaction section. Sandia National Laboratories is providing similar resources for conducting sulfuric acid decomposition, and GA has supplied an apparatus for decomposition of hydriodic acid. Some integration of sections has taken place, and the experiment is expected to operate through fiscal year 2009. TRL 5 is expected to be achieved in 2009.

# 3.1 Test Objective

The objective of the test will be to design, construct and operate a test pilot plant at 70 kW. Each of the three sections, Bunsen reactor, H2SO4 Decomposition, and HI Decomposition will be scaled up from the ILS experiment. Successful testing of the pilot plant will result in the advancement to TRL 6 for the SI process.

#### 3.2 Test Description

The pilot plant will be 70 kW and have the following performance criteria:

- 1. Bunsen Reactor
  - a. Scaling: 20,000 nlph hydrogen equivalent
  - b. Minimum operation: 1000 hours
- 2. H<sub>2</sub>SO<sub>4</sub> Decomposition
  - a. Scaling: 20,000 nlph hydrogen equivalent
  - b. Catalyst life: 1000 hours
  - c. Minimum operation: 1000 hrs
- 3. HI Decomposition
  - a. Scaling: 20,000 nlph hydrogen
  - b. Catalyst life: 1000 hours
  - c. Minimum operation: 1000 hours

#### 3.3 Test Conditions

The plant will operate under the same process conditions as expected in full-scale facilities. Pressures, temperatures, materials of construction, and composition of process streams will all match design parameters for a full-scale plant.

# 3.4 Test Configuration/Set-up

The plant will be electrically powered, with no nuclear power plant interface. Some heat integration between sections may be attempted.

#### 3.5 Test Duration

As shown in section 3.1.2, operation of up to 1000 hours of continuous hydrogen production is expected. Design and validation steps prior to construction will likely take two years. Construction and shakedown are estimated to take one year. Once construction and equipment shakedown is complete, it is estimated that the pilot plant will operate over the course of one year. Post-test evaluation and analysis should be complete within 6 months of conclusion of test operations.

#### 3.6 Proposed Test Location

A national laboratory site would be most suitable for location of the pilot plant. INL and SNL are recommended as primary candidates. Capabilities at the national laboratories for conducting hydrogen plant testing include:

- Facilities and resources for conducting long-term testing
- Analytical equipment for product and effluent characterization
- On-site engineering support
- On-site grinding, polishing, welding, shearing, machining, sawing

#### 3.7 Pilot Plant Test Measured Parameters

The following parameters would be included in the evaluation of the performance of the pilot plant:

- Length of runs
- Number of runs
- Acid purities exiting Bunsen section
- Consistency or variation in production rates from each section
- Quantity and composition of waste products
- Catalyst life

- Hydrogen flowrates
- Hydrogen purity
- Hydrogen outlet pressure

# 3.8 Data Requirements

Instruments for data capture shall be calibrated and certified for use under the GA ISO 9001 Quality Assurance Level II program, or under an equivalent method. Required accuracy for each device or method shall be determined during the design phase of the pilot plant program.

#### 3.9 Test Evaluation Criteria

Table 3 outlines preliminary criteria for evaluation of pilot plant performance.

**Table 3. Pilot Plant Performance Criteria** 

Sulfur-lodine Pilot Plant Performance Criteria	
Minimum dispensing pressure (psig)	300
% Hydrogen	> 98%
CO2 (ppm)	< 100
CO (ppm)	< 1
Sulfur (ppb)	< 10
Ammonia (ppm)	<1
Non-methane hydrocarbons (ppm)	< 100
Total of Oxygen, Nitrogen and Argon (%)	< 2
Water (ppm) < 100	
Minimum plant operating duration (hours) 1000	
Hydrogen production rate (nlph)	20,000

# 3.10 Supplementary Tests

Supplemental tests on auxiliary equipment, such as pumps or heat exchangers, may be conducted as necessary to determine parameters such as life cycle and corrosion resistance. Controls systems will be evaluated for safety and effectiveness.

#### 4 TEST PROGRAM TO ADVANCE TO TRL 7

TRL 7 definition: Subsystem integrated into a system for integrated engineering scale demonstration in a relevant environment.

A SI pilot plant will be constructed at a site to be determined. The plant will be electrically heated or coupled to a nuclear heat source, and it will be composed of materials of construction expected to be used for use in full-scale plants.

#### 4.1 Test Objective

The objective of the test will be to design, construct and operate a test engineering scale plant at 1.5 MW. Each of the three sections, Bunsen reactor, H<sub>2</sub>SO<sub>4</sub> Decomposition, and HI Decomposition will be scaled up from the pilot plant. Successful testing of the engineering scale plant will result in the advancement to TRL 7 for the SI process.

# 4.2 Test Description

The engineering scale plant will be 1.5 MW and have the following performance criteria:

- 1. Bunsen Reactor
  - a. Scaling: 425,000 nlph hydrogen equivalent
  - b. Minimum operation: 2500 hours
- 2. H<sub>2</sub>SO<sub>4</sub> Decomposition
  - a. Scaling: 425,000 nplh hydrogen equivalent
  - b. Catalyst life: 2500 hours
  - c. Minimum operation: 2500 hours
- 3. HI Decomposition
  - a. Scaling: 425,000 nlph hydrogen
  - b. Catalyst life: 2500 hours
  - c. Minimum operation: 2500 hours

#### 4.3 Test Conditions

The plant will operate under the same process conditions as expected in full-scale facilities. Pressures, temperatures, materials of construction, and composition of process streams will all match design parameters for a full-scale plant.

# 4.4 Test Configuration/Set-up

The plant could be electrically powered and if possible will be constructed at the proposed Component Test Facility at INL. Some heat integration between sections will be attempted.

#### 4.5 Test Duration

As shown in section 4.1.2, operation of up to 2500 hours of continuous hydrogen production is expected. Design and validation steps prior to construction will likely take three years. Construction and shakedown are estimated to take two years. Once construction and equipment shakedown is complete, it is estimated that the engineering demonstration plant will operate over the course of two years. Post-test evaluation and analysis should be complete within 6 months of conclusion of test operations.

#### 4.6 Proposed Test Location

A national laboratory site would be most suitable for location of the engineering scale plant. The proposed Component Test Facility at INL would be the optimal location for an effective evaluation of the engineering scale plant.

#### 4.7 Measured Parameters

The following parameters would be included in the evaluation of the performance of the engineering scale plant:

- Length of runs
- Number of runs
- Acid purities exiting Bunsen section
- Consistency or variation in production rates from each section
- Quantity and composition of waste products
- Catalyst life
- Thermal efficiency if significant heat integration is attempted
- Hydrogen flowrates
- Hydrogen purity
- Hydrogen outlet pressure

#### 4.8 Data Requirements

Instruments for data capture shall be calibrated and certified for use under the GA ISO 9001 Quality Assurance Level II program, or under an equivalent method. Required accuracy for each device or method shall be determined during the design phase of the engineering-scale plant program.

# 4.9 Test Evaluation Criteria

Table 4 outlines preliminary criteria for evaluation of engineering scale plant performance.

Table 4. Engineering Demonstration Plant Performance Criteria

Sulfur-Iodine Engineering Scale Plant Performance Criteria		
Minimum dispensing pressure (psig)	300	
% Hydrogen	> 98%	
CO2 (ppm)	< 100	
CO (ppm)	< 1	
Sulfur (ppb)	< 10	
Ammonia (ppm)	< 1	
Non-methane hydrocarbons (ppm)	< 100	
Total of Oxygen, Nitrogen and Argon (%)	< 2	
Water (ppm) < 100		
Minimum plant operating duration (hours) 2500		
Hydrogen production rate (nlph)	425,000	

# 4.10 Supplementary Tests

Supplemental tests on auxiliary equipment, such as pumps or heat exchangers, may be continued as necessary to refine parameters such as life cycle and corrosion resistance. Controls systems will be evaluated for safety and effectiveness. Evaluation of performance of heat pump vapor recompression equipment may occur during engineering scale operations.

#### 5 TEST PROGRAM TO ADVANCE TO TRL 8

TRL 8 definition: Integrated prototype of the system is demonstrated in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. Analyses, if used, support extension of demonstration to all design conditions. Analysis methods verified and validated. Technology issues resolved pending qualification (for nuclear application, if required). Demonstrated readiness for hot startup.

A SI prototype plant will be constructed at the NGNP site. The plant will be coupled to the NGNP nuclear heat source via an intermediate heat exchanger, and it will be composed of materials of construction expected to be used for use in commercial-scale plants.

# 5.1 Test Objective

The objective of the test will be to design, construct and operate a prototype plant at 15 MW. Each of the three sections, Bunsen reactor, H<sub>2</sub>SO<sub>4</sub> Decomposition, and HI Decomposition will be scaled up from the engineering scale plant. Successful testing of the prototype plant coupled with the NGNP will result in the advancement to TRL 8 for the SI process.

#### 5.2 Test Description

The prototype plant will be 15 MW and have the following performance criteria:

- 1. Bunsen Reactor
  - a. Scaling: 4,250,000 nlph equivalent
  - b. Minimum operation: 25,000 hours
- 2. H<sub>2</sub>SO<sub>4</sub> Decomposition
  - a. Scaling: 4,250,000 nlph equivalent
  - b. Catalyst life: 25,000 hours
  - c. Minimum operation: 25,000 hours
- 3. HI Decomposition
  - a. Scaling: 4,250,000 nlph
  - b. Catalyst life: 25,000 hours
  - c. Minimum operation: 25,000 hours

#### 5.3 Test Conditions

The plant will operate under the same process conditions as expected in commercial-scale facilities. Pressures, temperatures, materials of construction, and composition of process streams will all match design parameters for a commercial-scale plant.

# 5.4 Test Configuration/Set-up

The plant will be coupled to the NGNP nuclear heat source. Extensive heat integration to maximize thermal efficiency will be included in the design.

#### 5.5 Test Duration

As shown in section 5.1.2, operation of up to 25,000 hours of continuous hydrogen production is expected. Design and validation steps prior to construction will likely take three years. Construction and shakedown are estimated to take three years. Once construction and equipment shakedown is complete, it is estimated that the prototype plant will operate over the course of three years. Post-test evaluation and analysis should be complete within 12 months of conclusion of test operations.

#### 5.6 Proposed Test Location

The prototype plant will be built at the NGNP site.

#### 5.7 Measured Parameters

The following parameters would be included in the evaluation of the performance of the prototype plant:

- Length of runs
- Number of runs
- Acid purities exiting Bunsen section
- Consistency or variation in production rates from each section
- Quantity and composition of waste products
- Catalyst life
- Thermal efficiency
- Hydrogen flowrates
- Hydrogen purity
- Hydrogen outlet pressure

# 5.8 Data Requirements

Instruments for data capture shall be calibrated and certified for use under the GA ISO 9001 Quality Assurance Level II program, or under an equivalent method. Required accuracy for each device or method shall be determined during the design phase of the pilot plant program.

# 5.9 Test Evaluation Criteria

Table 5 outlines preliminary criteria for evaluation of engineering scale plant performance.

Table 5. Prototype Plant Performance Criteria

Sulfur-Iodine Engineering Scale Plant Performance Criteria		
Minimum dispensing pressure (psig) 300		
% Hydrogen	> 98%	
CO2 (ppm)	< 100	
CO (ppm)	< 1	
Sulfur (ppb)	< 10	
Ammonia (ppm) < 1		
Non-methane hydrocarbons (ppm)	< 100	
Total of Oxygen, Nitrogen and Argon (%) < 2		
Water (ppm) < 100		
Minimum plant operating duration (hours) 25,000		
Hydrogen production rate (nlph) 4,250,000		

# 5.10 Supplementary Tests

Supplemental tests on auxiliary equipment, such as pumps or heat exchangers, may be continued as necessary from engineering demonstration scale to refine parameters such as life cycle and corrosion resistance. Controls systems will be evaluated for safety and effectiveness. Complete evaluation of performance of heat pump vapor recompression equipment will occur during prototype plant operations.

# **6 TEST DELIVERABLES**

- Bunsen reaction section design analysis.
- Sulfuric acid decomposition section design analysis.
- Hydriodic acid decomposition section design analysis.
- Design of controls systems for integrating the Hydrogen Production System with the nuclear plant .
- Hydrogen Production System Component Test Development Plan
- Test specifications
- Test reports
- An optimized Hydrogen Production System design with acceptable performance, safety and reliability criteria.

# 7 COST, SCHEDULE, AND RISK

The development test program for the HPS must be integrated with the design and fabrication effort for the MHTGR program to assure that conceptual design, final design, production hardware, etc., are available in a timely fashion. This document assumes a test program will arise, with adequate design and development funding, for completion of development testing prior to the start of fabrication. However, all work is subject to DOE contract award and may be supplied or performed by other selected vendors. Completing the test program, described herein, will provide greater confidence in the design prior to the release for fabrication.

#### 7.1 Cost

Table 6 below is a summary of estimated costs for development of the SI cycle from TRL 5 to TRL 8 upon the successful operation of the prototype plant at NGNP.

Test Category <sup>(1)</sup>	Test	Test Costs (000's) <sup>(2)</sup>
Pilot Plant	Bunsen Reaction Section	\$20.0
	Sulfuric Acid Decomposition Section	\$12.1
	Hydriodic Acid Decomposition Section	\$23.2
Engineering Demonstration Plant	Bunsen Reaction Section	\$31.9
	Sulfuric Acid Decomposition Section	\$22.6
	Hydriodic Acid Decomposition Section	\$26.5
	Bunsen Reaction Section	\$58.9
Prototype Plant	Sulfuric Acid Decomposition Section	\$42.6
	Hydriodic Acid Decomposition Section	\$80.2
	Total	\$318

<sup>(1)</sup> HPS DDN's supported: HPS-SAD-1, 2,3,4,5,6,7,8,9,10,11,12,13,14,15; HPS-BUN-1,2,3,4,5,6,7; HPS-HID-01,2,3,4,5,6,7,8,9; HPS-FUS-1,2,3; HPS-PPU-1,2; HPS-PCN-1,2,3. See Section 8.

These cost estimates are preliminary and include installation, labor, engineering, and operating costs. Components were individually sized for the relevant scales and the capital cost for each component was calculated using the method of Guthrie (Guthrie, KM, Capital cost estimating, Chemical Engineering, March 24, 1969, 114-142).

Two factors have the potential to significantly reduce development costs. First, there is an effort to obtain more complete thermodynamic data for the chemistries in the hydriodic acid (HI)

<sup>(2)</sup> In 2005 dollars.

decomposition section. Initial work done at CEA in 2007 suggests that energy requirements for vaporizing mixtures containing HI are overestimated with current thermodynamic models. If this can be confirmed with further experimental work, it could potentially eliminate costly vapor recompression equipment required for energy recovery in the HI decomposition section. This equipment comprises the single largest capital cost contributor for a SI plant at this time. Electrical demand for the cycle would drop by an order of magnitude or more. This would also significantly reduce hydrogen production costs in a commercial scale plant. HPS DDN HPS-HID-02 describes the requirement for further work in this area.

Second, preliminary discussions have been held between GA and the Japan Atomic Energy Agency (JAEA) regarding development of a SI plant, on the scale of the NGNP prototype that would be coupled to the High Temperature Test Reactor (HTTR) currently operating in Japan. This gas reactor has achieved operation at up to 950°C. It may be possible for DOE to share development costs for the cycle through a collaborative effort with JAEA in this area. Development times would likely be reduced, as the reactor is already operating.

#### 7.2 Schedule

To satisfy an NGNP plant start-up schedule of 2021, completion of each event should correspond to the schedule in Figure 5. The schedule may shift depending on the NGNP reactor start-up schedule.

# 7.3 **Risk**

The technology required to produce high-pressure hydrogen from a thermochemical plant coupled with nuclear power has not yet been demonstrated beyond laboratory bench scale. Development risks increase with plant capacity. Such risks should be mitigated by implementation of an early test program, developed to check feasible limits of operation. Current operation of the ILS device is the initial stage of such an effort. Fall back options for state-of-the-art prototypal components should be identified in parallel at each stage of development. In particular, development work in the area of HI decomposition chemistry and modeling has the potential for a very high rate of return.

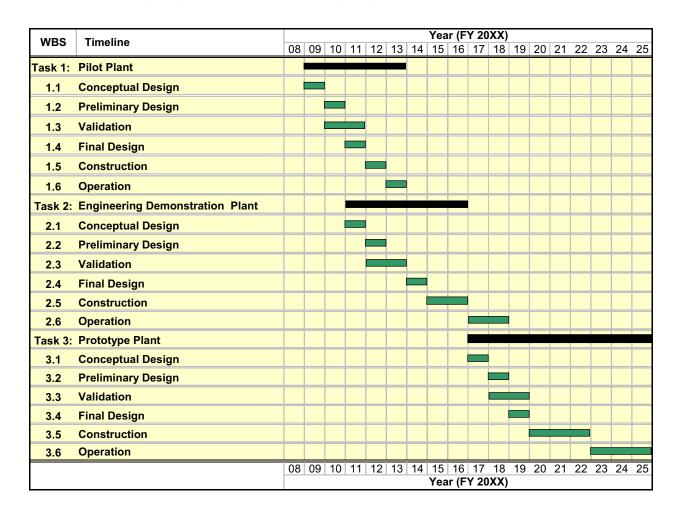


Figure 5. SI HPS Testing Schedule

# 8 DESIGN DATA NEEDS

Table 6 in Section 7.1 refers to HPS design data needs (DDNs). These DDNs have been proposed by the Shaw Group and are listed in Table 7.

Table 7. Shaw Group Design Data Needs for the HPS

DDN	Title
HPS-SAD-01	Confirm Thermodynamic Data for the Sulfuric Acid Decomposition Process
HPS-SAD-02	Develop a Commercial Sulfuric Acid Decomposition Catalyst
HPS-SAD-03	Gather Decomposition Reaction Kinetics Data
HPS-SAD-04	Test Silicon Carbide and other Ceramic Material in Decomposition Service
HPS-SAD-05	Test Alloy 230 and Alloy 617 in a High Temperature Sulfuric Acid, Sulfur Dioxide, and Oxygen Atmosphere.
HPS-SAD-06	Develop a Method to Bond Alloy 230 or Alloy 617 or Similar Materials to Silicon Carbide and other Ceramics.
HPS-SAD-07	Develop Materials to Seal the Joints between Ceramic Decomposer Elements and the Metallic Tube Sheet or Vessel.
HPS-SAD-08	Test a Pilot-Scale Decomposer.
HPS-SAD-09	Provide Data Supporting a Design Code Case
HPS-SAD-10	Develop Gasket Materials and Design
HPS-SAD-11	Develop Seal Materials and Design
HPS-SAD-12	Develop Welding Materials
HPS-SAD-13	Develop Cladding and Coating Materials
HPS-SAD-14	Develop Piping Materials and Design Methods
HPS-SAD-15	Measure the Height Equivalent to a Theoretical Plate (HETP) for the Concentrator (Vacuum Tower)
HPS-BUN-01	Confirm Thermodynamic Data for the Bunsen Reaction Process including Phase Equilibria
HPS-BUN-02	Gather Kinetic and Mass Transfer Data for the Bunsen Reaction in the proposed reactor configuration
HPS-BUN-03	Develop Gasket Materials and Design for Bunsen Reaction Environment
HPS-BUN-04	Develop Seal Materials and Design for Bunsen Reaction Environment
HPS-BUN-05	Develop Welding Materials for Bunsen Reaction Environment
HPS-BUN-06	Develop Cladding and Coating Materials for Bunsen Reaction Environment
HPS-BUN-07	Develop Piping Materials and Design Methods for Bunsen Reaction Environment
HPS-HID-01	Demonstrate Hydroiodic Acid Reactive Distillation Decomposition in Principle
HPS-HID-02	Confirm Thermodynamic Data for the Hydroiodic Acid Decomposition Process including Phase Equilibria
HPS-HID-03	Develop commercial HI Decomposition Catalyst

DDN	Title
HPS-HID-04	Gather Kinetic and Mass Transfer Data for the Hydroiodic Acid Decomposition in the proposed reactor configuration based on the commercial catalyst
HPS-HID-05	Develop Gasket Materials and Design for Hydroiodic Acid Decomposition Environment
HPS-HID -06	Develop Seal Materials and Design for Hydroiodic Acid Decomposition Environment
HPS-HID -07	Develop Welding Materials for Hydroiodic Acid Decomposition Environment
HPS-HID -08	Develop Cladding and Coating Materials for Hydroiodic Acid Decomposition Environment
HPS-HID-09	Develop Piping Materials and Design Methods for Hydroiodic Acid Decomposition Environment
HPS-FUS-01	Identify Critical Impurities and Determine Critical Component Tolerance
HPS-FUS-02	Develop Feed Water Purification Methods
HPS-FUS-03	Develop Process Fluid Purification Methods
HPS-PPU-01	Identify Product Impurities
HPS-PPU-02	Test Product Purification Methods
HPS-PCN-01	Test Sensors in the Pilot Plant
HPS-PCN-02	Develop Valves for High-Temperature Acid Service
HPS-PCN-03	Test Valves in the Pilot Plant

